

Two photon couplings of the lightest isoscalars from BELLE data

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Abstract

Amplitude Analysis of two photon production of $\pi\pi$ and $\bar{K}K$, using S-matrix constraints and fitting all available data, including the latest precision results from Belle, yields a single partial wave solution up to 1.4 GeV. The two photon couplings of the $\sigma/f_0(500)$, $f_0(980)$ and $f_2(1270)$ are determined from the residues of the resonance poles.

Keywords: $\gamma\gamma$ scattering, Light mesons, Partial-wave analysis.

1. Introduction

Two photon reactions play a special role in the study of QCD: photons pick out the charged components of hadrons and so probe their structure. In this Letter we present the results of a comprehensive Amplitude Analysis of all data on $\gamma\gamma \rightarrow \pi^+\pi^-$, $\pi^0\pi^0$, $\bar{K}K$ up to 1.4 GeV. This includes for the first time the high statistics data from Belle on $\pi^+\pi^-$ [1], $\pi^0\pi^0$ [2] and the very new $K_s K_s$ [3] results in a coupled channel analysis. The data have limited angular coverage and no polarization information. Nevertheless, unitarity links these two photon reactions to the corresponding meson-meson scattering processes. When combined with the other basic S-matrix principles of analyticity and crossing, these constraints make up for the limitations of the data, and make an Amplitude Analysis feasible. At present this can be implemented where the $\pi\pi$ and $\bar{K}K$ channels saturate unitarity, which is roughly up to 1.4-1.5 GeV. At higher energies multi-meson production becomes important, for which we do not yet have precise enough information to extend the analysis further. The hadronic amplitudes we need are constructed from the classic meson-meson scattering results on $\pi\pi \rightarrow \pi\pi$ from CERN-Munich [4], and the $\pi\pi \rightarrow \bar{K}K$ from Argonne [5] and Brookhaven [6], combined with recent dispersive analyses of all of these [7, 8]. These are the key inputs to unitarity for the two photon production of these same hadronic final states and to the partial wave dispersion relations we use to connect the low energy theorem of QED for pion Compton scattering with the near threshold $\gamma\gamma \rightarrow \pi\pi$. The 3000 two photon data points for the $\pi\pi$ channels and 350 data on $\bar{K}K$, covering both integrated and differential

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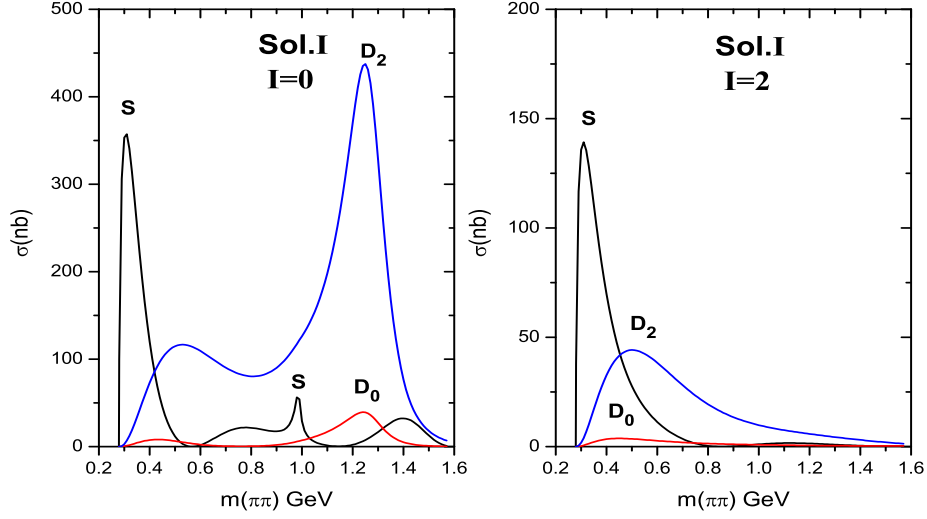


Figure 1: Individual partial wave components of the $\gamma\gamma \rightarrow \pi\pi$ integrated cross-section.

cross-sections, are fitted and a set of solutions found. Being a coupled channel analysis, what makes the solution presented here close to unique is the inclusion of data on the $\gamma\gamma \rightarrow \bar{K}K$ channels. The older kaon production data, largely from experiments at DESY, are rather sparse, yet restrict the solution space. When combined with the latest $K_s K_s$ results from Belle, which are the first with accurate coverage from threshold upwards with angular information out to $\cos\theta = 0.6 - 0.8$, the range of solutions shrinks still further to the Amplitude we present here.

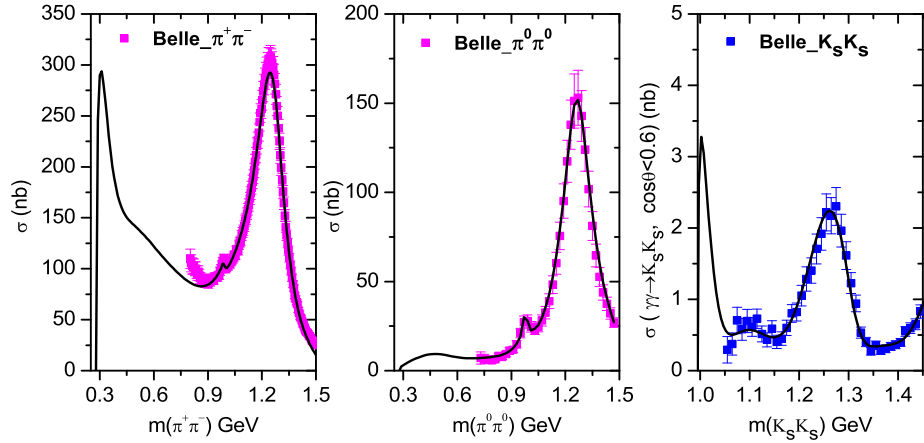


Figure 2: Solution. I compared with the integrated cross-section datasets of Belle. The $\gamma\gamma \rightarrow \pi^+\pi^-$ process [1] are integrated over $|\cos\theta| \leq 0.6$, $\gamma\gamma \rightarrow \pi^0\pi^0$ [2] is 0.7 and for $\gamma\gamma \rightarrow K_s K_s$ [3] it is 0.6.

2. Two photon couplings

Having data on both the charged and neutral pion final states allows a separation of the $I = 0$ and 2 components of the $\gamma\gamma \rightarrow \pi\pi$ amplitudes, and the determination of the individual partial waves with helicity-0 and 2 within narrower ranges than previously possible. The $\pi\pi$ partial wave cross-sections for $J = 0, 2$ are shown in Fig. 1. How these describe the integrated cross-sections is shown in Fig. 2 for $\pi^+\pi^-$, $\pi^0\pi^0$ and $K_s K_s$ production. While only the comparison with Belle data is shown here, our Amplitudes describe all the available data from Mark II, CELLO, Crystal Ball, TASSO, ARGUS and TPC [9]-[19] too. While only even isospins occur for the $\pi\pi$ channel, the K^+K^- and $\bar{K}^0 K^0$ have $I = 0, 1$. The isoscalar channels are highly constrained by unitarity. However, the isovector channel has to be freely parametrized. Nevertheless, the input of the $\bar{K}K$ data fixes the isoscalar partial waves. The way our amplitudes describe the angular distributions for $\pi^+\pi^-$, $\pi^0\pi^0$ and $K_s K_s$ are illustrated in Fig. 3 at a number of representative energies. The complete datasets used, the treatment of systematic errors

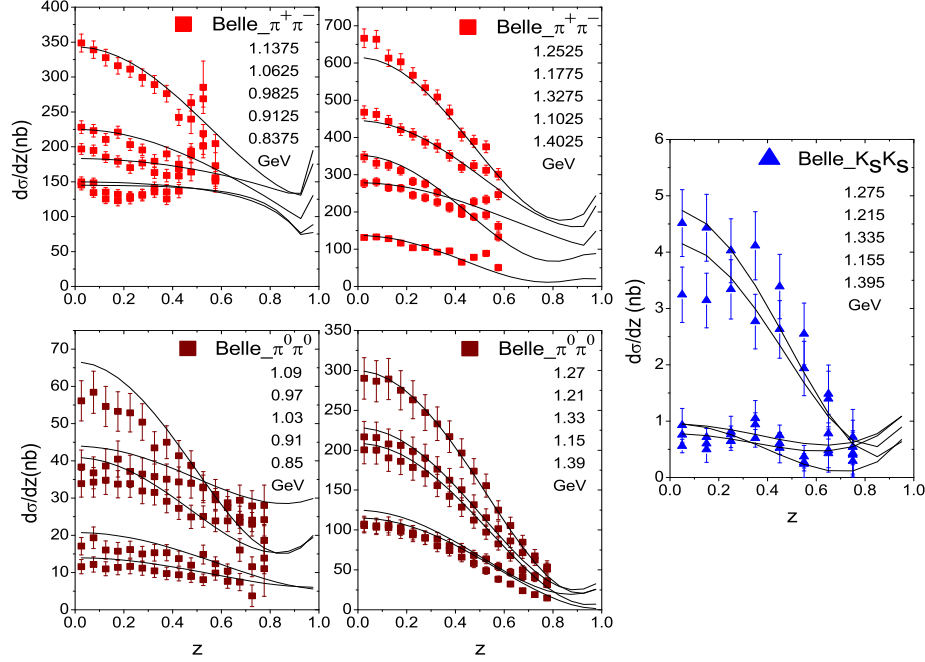


Figure 3: Solution. I compared with the differential cross-section datasets of Belle. The $\gamma\gamma \rightarrow \pi^+\pi^-$ process is from [1], $\gamma\gamma \rightarrow \pi^0\pi^0$ from [2] and for $\gamma\gamma \rightarrow K_s K_s$ from [3]. The c.m. energies (in GeV) given on the right in each plot are listed in order of the height of the differential cross-sections for the data and amplitude solution curves at $z = 0$.

and the dispersive technology used, together with the full results, will be described in a longer paper [20].

The outcome of this analysis is the set of partial wave amplitudes. In turn, these fix the two photon couplings of the resonance poles that occur in these channels. These are

dominated by the $\sigma/f_0(500)$, $f_0(980)$ and $f_2(1270)$. The residues of these poles on the appropriate nearby sheet of the energy plane determine the two photon coupling $g_{\gamma\gamma}$ for each state. The two photon width, $\Gamma(R \rightarrow \gamma\gamma)$, is readily defined for an isolated, narrow state from its residue at a nearby pole in the complex energy plane, well-separated from threshold cuts. For the states that dominate the channels studied here, that are broad and overlap with each other and with strongly coupled thresholds, we still use the same definition, viz:

$$\Gamma(R \rightarrow \gamma\gamma) = \frac{\alpha^2}{4(2J+1)m_R} |g_{\gamma\gamma}|^2, \quad (1)$$

where α is the usual QED fine structure constant, J is the spin of the resonance, and m_R its mass. Here we take m_R to be the modulus of the pole position in the energy plane. Other definitions are folded into the uncertainties. This $\Gamma(R \rightarrow \gamma\gamma)$ is, of course, **not** a physical quantity, but merely an intuitive way of re-expressing $|g_{\gamma\gamma}|$. These values are listed in Table 1.

State	Sh	pole locations (GeV)	$g_{\gamma\gamma} = g e^{i\varphi}$			$\Gamma(f_J \rightarrow \gamma\gamma)$ (keV)	$\lambda = 0$ fraction %
			J_λ	$ g $ (GeV)	φ (°)		
$f_2(1270)$	III	$1.267 - i0.108$	D_0	0.35 ± 0.03	168 ± 6	2.95 ± 0.43	8.6 ± 1.7
			D_2	1.13 ± 0.08	173 ± 6		
$\sigma/f_0(500)$	II	$0.441 - i0.272$	S	0.26 ± 0.01	107 ± 3	2.06 ± 0.22	100
$f_0(980)$	II	$0.995 - i0.042$	S	0.16 ± 0.01	185 ± 3	0.32 ± 0.03	100

Table 1: The isoscalar resonance poles and their two photon residues (both magnitude and phase) from our Amplitude Solution are listed. These residues can be interpreted in terms of two-photon partial widths using Eq. (1). These are tabulated in keV. For each the fraction of the width provided by helicity zero is given: for the scalar resonances, it is, of course, 100%.

3. Discussion

Model calculations have been made for these states depending on their “primordial” composition. How these are related to those in the real world of important meson final state interactions do not yet exist beyond models. Kaon loop modelling by Achasov and collaborators [21] favors a tetraquark composition for the $f_0(980)$, while we would see a $\bar{K}K$ molecular structure as more appropriate [22]. It is such considerations that make a comparison with the two photon production of the $a_0(980)$ of special interest. However, results of comparable precision for isovector states must await a corresponding coupled channel analysis combining data on $\gamma\gamma \rightarrow \pi^0\eta$, K^+K^- and \bar{K}^0K^0 with that on $\pi\pi$. While the two photon production of $\pi\pi$ and $\eta\pi$ channels, of course, access different isospins,

the $\overline{K}K$ channels involve both $I = 0, 1$. Thus a larger global analysis would be required, which would inevitably involve multi-pion channels too. This is beyond our present ambitions.

Other analyses have combined dispersion relations with unitarity and hadronic scattering information, with the same basic philosophy as we have followed here. Calculations by Garcia-Martin and Moussallam [23] have assumed that the crossed-channel exchanges, namely states in $\gamma\pi$ scattering, have known couplings and hence the direct channel $\gamma\gamma \rightarrow \pi\pi$ cross-sections can be predicted up to at least 1 GeV. As we shall discuss in a separate, more technical paper, single particle exchange (beyond the crucial one pion exchange of the Born amplitude) is likely a poor approximation to the multi-meson exchanges that control the details of the left hand cut amplitude. Hoferichter, Phillips and Schat [24] have used Roy-Steiner equations deduced from dispersion relations on hyperbolae to constrain the $\gamma\gamma \rightarrow \pi\pi$ amplitudes. Their analysis does not attempt to fit experimental information beyond 1 GeV directly. Here we perform an Amplitude Analysis within a corresponding S-matrix framework, but in which data are used directly to delineate the partial waves. From these we then determine the $\gamma\gamma$ couplings of each resonant pole. Knowledge of the on-shell two photon production of hadrons with an element of precision is an increasingly important contribution to reducing the uncertainties in hadronic light-by-light scattering in quantities such as $g - 2$ of the muon.

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References

- [1] T. Mori *et al.* [Belle], Phys. Rev. **D75** (2007) 051101, arXiv:0610038 [hep-ex]; J. Phys. Soc. Jap. **76** (2007) 074102, arXiv:0704.3538 [hep-ph].
- [2] K. Abe *et al.* [Belle], arXiv:0711.1926 [hep-ex]; S. Uehara *et al.* [Belle], Phys. Rev. **D78** (2008) 052004, arXiv:0805.3387 [hep-ex]; S. Uehara *et al.* [Belle], Phys. Rev. **D79** (2009) 052009, arXiv:0903.3697 [hep-ex].
- [3] S. Uehara *et al.* [Belle], PTEP (2013) 123C01, arXiv:1307.7457 [hep-ex].
- [4] B. Hyams, *et al.*, Nucl. Phys. **B64** (1973) 134; G. Grayer, *et al.*, Nucl. Phys. **B75** (1974) 189; B. Hyams, *et al.*, Nucl. Phys. **B100** (1975) 205.
- [5] D. Cohen, D. S. Ayres, R. Diebold, S. L. Kramer, A. J. Pawlicki, and A. B. Wicklund, Phys. Rev. **D22** (1980) 2595.
- [6] A. Etkin *et al.*, Phys. Rev. **D25** (1982) 1786.

- [7] R. García- Martín, R. Kamiński, J. R. Peláez, J. Ruiz de Elvira, and F. J. Ynduráin, Phys. Rev. **D83** (2011) 074004, arXiv:1102.2183 [hep-ph]; Phys. Rev. **D77** (2008) 054015, arXiv:0710.1150 [hep-ph]; R. Kamiński, J. R. Peláez, and F. J. Ynduráin, Phys. Rev. **D74** (2006) 014001, Erratum-ibid. **D74** (2006) 079903, arXiv:0603170 [hep-ph]; J.R. Peláez and F. J. Ynduráin, Phys. Rev. **D71** (2005) 074016, arXiv:0411334 [hep-ph];
- [8] P. Buttiker, S. Descotes-Genon and B. Moussallam, Eur. Phys. J. **C33** (2004) 409, arXiv:0310283 [hep-ph].
- [9] J. Boyer *et al.* [Mark II], Phys. Rev. **D42** (1990) 1350.
- [10] J. Harjes, Ph.D. thesis, submitted to the University of Hamburg.
- [11] H.J. Behrend *et al.* [CELLO], Z. Phys. **C56** (1992) 381.
- [12] H. Marsiske *et al.*, [Crystal Ball], Phys. Rev. **D41** (1990) 3324.
- [13] J.K. Bienlein *et al.*, [Crystal Ball], Proc. *IX Int. Workshop on Photon-Photon Collisions*, San Diego 1992, ed. D. Caldwell and H.P. Paar (World Scientific, 1992), pp. 241.
- [14] H. Albrecht *et al.* [ARGUS], Z. Phys. **C48** (1990) 183.
- [15] M. Althoff *et al.* [TASSO], Phys. Lett. **B121** (1983) 216.
- [16] H. Aihara *et al.* [TPC], Phys. Rev. Lett. **57** (1986) 404.
- [17] K. Abe *et al.* [Belle], Eur. Phys. J. **C32** (2004) 323, arXiv:0309077 [hep-ex].
- [18] H.J. Behrend *et al.* [CELLO], Z. Phys. **C31** (1989) 91.
- [19] M. Althoff *et al.* [TASSO], Z. Phys. **C29** (1986) 189.
- [20] L. Y. Dai and M. R. Pennington, in preparation.
- [21] N.N. Achasov and G. N. Shestakov, Phys. Rev. **D77** (2008) 074020, arXiv:0712.0885 [hep-ph]; JETP. Lett. **88** (2008) 295, arXiv:0810.2201 [hep-ph]; JETP. Lett. **96** (2012) 493, arXiv:1210.0739 [hep-ph]; Phys. Usp. **54** (2011) 799, arXiv:0905.2017 [hep-ph].
- [22] M.R. Pennington, AIP Conf. Proc. **1257** (2010) 27, arXiv:1003.2549 [hep-ph].
- [23] R. Garcia-Martin, and B. Moussallam, Phys. Rev. **D83** (2011) 054008, arXiv:1011.4446 [hep-ph].
- [24] M. Hoferichter, D.R. Phillips and C. Schat, Eur. Phys. J. **C71** (2011) 1743, arXiv:1106.4147 [hep-ph].